NAVAL POSTGRADUATE SCHOOL
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THESIS

RECENT ADVANCES IN THE TECHNOLOGY OF
MICROWAVE DEVICES EMPLOYED IN RADAR
SYSTEMS, AND THE IMPACT OF THESE
TECHNOLOGIES ON POTENTIAL IMPROVEMENTS
TO RADAR SYSTEM PERFORMANCE

by

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13. ABSTRACT
This thesis is a study of the recent advances in microwave device technology that can be applied to the improvement of phased array radar systems which are able to provide multifunction capabilities to navy ships. The study was undertaken to provide guidance to military planners who are often required to keep abreast of developments in a rapidly changing field of technology. The fact that even the most advanced presently-used radar systems in the navy are based on five to ten year-old technology verifies the need for this study. Microwave Power Modules which combine vacuum tube and Solid State technology have been developed and have demonstrated advanced performance characteristics. Their advantages, such as very wide bandwidth and ability to operate at much higher ambient temperatures over that of the Solid State devices have opened up new opportunities for their use in Radar systems. However, output power capability of MPM while growing rapidly is still below the minimum level required for a phased array radar on board a midsize ship operating in confined waters. The present technology available however in Solid State Transmit Receive modules, does supply the capabilities needed for a realization of an active phased array radar. Such a system will enhance ships operational capabilities while achieving a reduction of the prime power consumption as well as in needed space. The applicability and characteristics of these devices are presented in this thesis.

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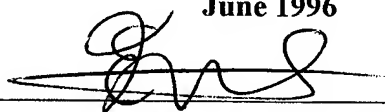Submitted in partial fulfillment
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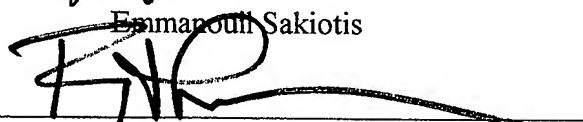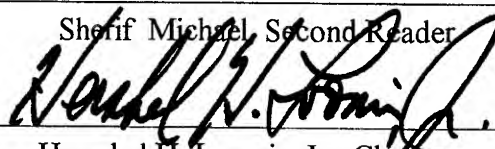## NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

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Microwave Power Modules which combine vacuum tube and Solid State technology have been developed and have demonstrated advanced performance characteristics. Their advantages, such as very wide bandwidth and ability to operate at much higher ambient temperatures over that of the Solid State devices have opened up new opportunities for their use in Radar systems. However, output power capability of MPM while growing rapidly, is still below the minimum level required for a phased array radar on board a midsize ship operating in confined waters.

The present technology available however in Solid State Transmit/Receive modules, does supply the capabilities needed for a realization of an active phased array radar. Such a system will enhance ships operational capabilities while achieving a reduction of the prime power consumption as well as in needed space. The applicability and characteristics of these devices are presented in this thesis.

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LIST OF SYMBOLS, ACRONYMS AND/OR ABBREVIATIONS

CIC	Combat Information Center
CW	Continuous Wave
DOD	Department Of Defense
ECM	Electronic Counter Measures
FET	Field Effect Transistor
HEMT	High Electron Mobility Transistor
HF	High Frequency
HPRF	High Pulse Repetition Frequency
IF	Intermediate Frequency
IEEE	Institute of Electrical and Electronics Engineers
ISAR	Inverse Synthetic Array Radar
ITU	International Telecommunications Union
LNA	Low Noise Amplifier
LPRF	Low Pulse Repetition Frequency
MMIC	Monolithic Microwave Integrated Circuit
MPM	Microwave power Modules
MPRF	Medium Pulse Repetition Frequency
MTBF	Mean Time Between Failures
MTI	Moving Target Indicator
MUD	Maximum Unambiguous Doppler
PPI	Plan Position Indicator
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
RCS	Radar Cross Section
RF	Radio Frequency

SAR	Synthetic Array Radar
SSAPAR	Solid State Active Phased Array Radar
SSM	Solid State Modules
T/R	Transmit/Receive
TWT	Traveling Wave Tube
TWTA	Traveling Wave Tube Amplifier
VHF	Very High Frequency
VLSI	Very Large Scale Integration
VTR	Vacuum Tube Radar

I. INTRODUCTION

The application of advanced technologies in military applications has pushed the radar system to the second position in the importance scale on a navy ship; right after the power plant. All shipboard navigation, weapons and defense systems depend on information received from the radar. This requires that the radar should be able to cooperate with the rest of the ship's systems and all should be customized to the specific task of the ship.

Technology provides todays ships with capabilities that ten years ago would have been characterized as "science fiction." The problem is that technology advances so fast these days that decision managers find it difficult to stay up-to-date. This thesis will try to provide a partial solution to this problem. It will focus on the radar needs of a midsize navy ship, such as a frigate or corvette, built to operate in confined waters, for example the Aegean sea, the Ionian sea or the Mediterranean; the environment that an Hellenic navy vessel might operate in. We will study whether new microwave device technology can improve the Radar system performance. We will first determine the type of Radar system that will be used to provide the needed capabilities. Then we will search the present microwave technology achievements to find the devices that will contribute to the Radar system performance improvement.

Initially the basic concept and a general description of the radar system will be reviewed to build a basis of understanding for the non-engineer reader. Then the required radar characteristics according to the ships mission will be outlined. The possible radar system configuration which could fulfill the needs for this mission will be examined. It will be shown that although technology provides various designs well suited for specific tasks, for the general multifunction radar in which we have a specific interest, the best available system is the Phased Array Radar. A comparison between active and passive phased array will reveal the superior performance characteristics of the active one. Finally the present

technological capability to provide the microwave devices needed to build the system will be explored. The possibility of using either Solid State Modules (SSM) or Microwave Power Modules (MPM) will be explored. Although MPM output power is still low, their advanced performance capabilities will be outlined, since they show a rapidly growing capability of increased output power and it is possible that within the next five years they will have reached the minimum output power level requirement needed in navy applications. Finally we will examine the present microwave device industry capability in providing Solid State Modules with the characteristics which will provide the active phased array radar system the presently required capabilities. The radar range equation will be used to verify that the characteristics of the provided SSM (operating frequency, output power, bandwidth, noise figure) meet or exceed the minimum requirements of the system. We will use as a baseline for performance comparison of the various radar types, a normalized maximum detection range capability.

A. BASIC RADAR SYSTEM CONCEPT

Most objects reflect radio waves similarly to the way they reflect light. Radar is a system that uses this fact to detect objects illuminated with radio waves, and to extract ranging information. When radar was first introduced, the major benefit it provided was the use of radio waves to detect objects at great distances under adverse weather, day or night. Now we have recognized many more advantages depending on the choice of frequency band, transmitted signal characteristics and signal processing of the reflected energy. In addition today's systems can provide operators with much more information than just target range and bearing. This includes target radial speed (through Doppler frequency shift of the echoes), small targets over large clutter, even target shape or ground mapping through high resolution radars. High resolution in range can be obtained with the use of short, or modulated pulses (both provide large bandwidth). For ground mapping we can use Synthetic Array Radars (SAR), and for target imaging, Inverse Synthetic Array Radars (ISAR).
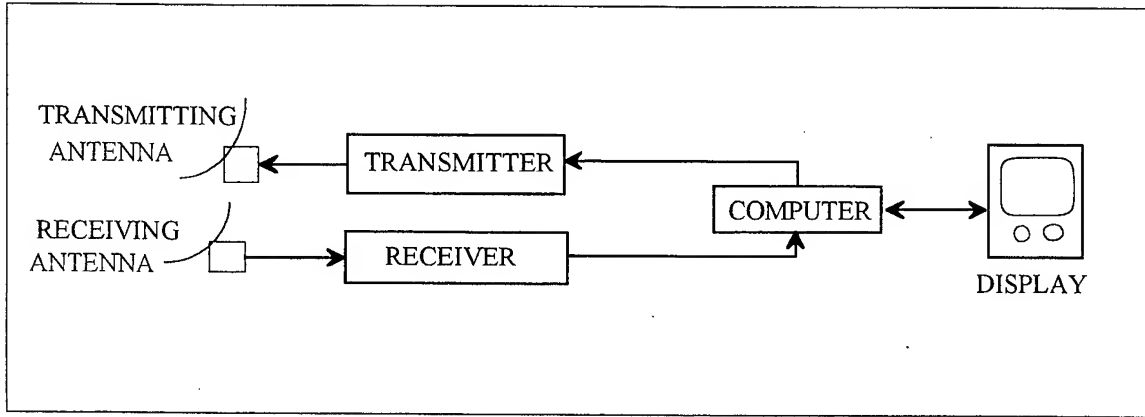
Figure 1.1. Basic Radar. [After Ref. 1].

An elementary radar block diagram (shown in Figure 1.1) would consist of a radio transmitter, a transmitting antenna, a receiving antenna (most of the times one antenna can fulfill both functions), a receiver tuned according to the transmitter, a computer and a display.

The transmitter generates radio waves which are radiated by the antenna; the receiver listens for echoes of the transmitted waves that have returned to the antenna; then proper signals (data) are fed to the computer for processing and finally the display uses the computer output to generate an image understandable by the user. Such a system has numerous applications; some of them are navigation, control and guidance of airplanes or missiles, surveillance, weather prediction or space exploration. There are many choices of components/devices to be used in the major building blocks mentioned above, depending on the application and the user.

For detecting the maximum range that an object can be detected, as a function of the characteristics of the transmitter, receiver, antenna, target and environment, there is a basic equation (Equation 1.1). We will use this equation in the following chapters to determine whether the Radar characteristics provided by existing devices meet the minimum requirements for a navy multifunction radar.

$$R_{\max} = \left[\frac{P_t G_t^2 \lambda^2 \sigma}{(4\pi)^3 k T_0 B_n F_n (S_0/N_0)_{\min}}\right]^{1/4} \qquad (1.1)$$

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where: P_t = transmitted power, watts

        G_t = antenna gain

        A_e = antenna effective aperture, m^2

        σ = target radar cross section, m^2

        $(S_o/N_o)_{min}$ = Minimum signal to noise ratio

        F_n = noise figure of receiver

        B_n = receiver bandwidth, Hz

        T_o = 290 °K

        k = Boltzmann's constant = 1.38×10^{-23} J/deg

where S_{min} = $k\, T_o\, B_n\, F_n\, (S_o/N_o)_{min}$ = Minimum detectable signal, watts.

From the radar equation one can conclude that for best radar system performance we need high power, high antenna gain, but low noise. There is a trade off between competing factors so, we can not have a single radar which is perfect for all applications.

B. EXPANDED VIEW OF BASIC RADAR SYSTEM

In order to further understand the Radar system and see where the devices that will be mentioned later in this chapter fit in, a more in depth block diagram than the one of Figure 1.1, is provided in Figure 1.2. The majority of today's applications use a waveform generator, a separate power amplifier, a single antenna (which requires the use of a duplexer to act as a rapid switch for incoming and outgoing signals so the time sharing of the single antenna becomes possible). There is a low noise RF amplifier down the line, followed by a mixer, which is also fed by a local oscillator. The received signal at the mixer output is at lower frequency and is then fed in the IF amplifier and finally passing through a matched filter, to an envelope or phase detector. Possible identified target echoes are amplified in the video amplifier so they can be displayed to the operator, or a computer or another cooperating system. A further description of the individual radar system components mentioned above follows.

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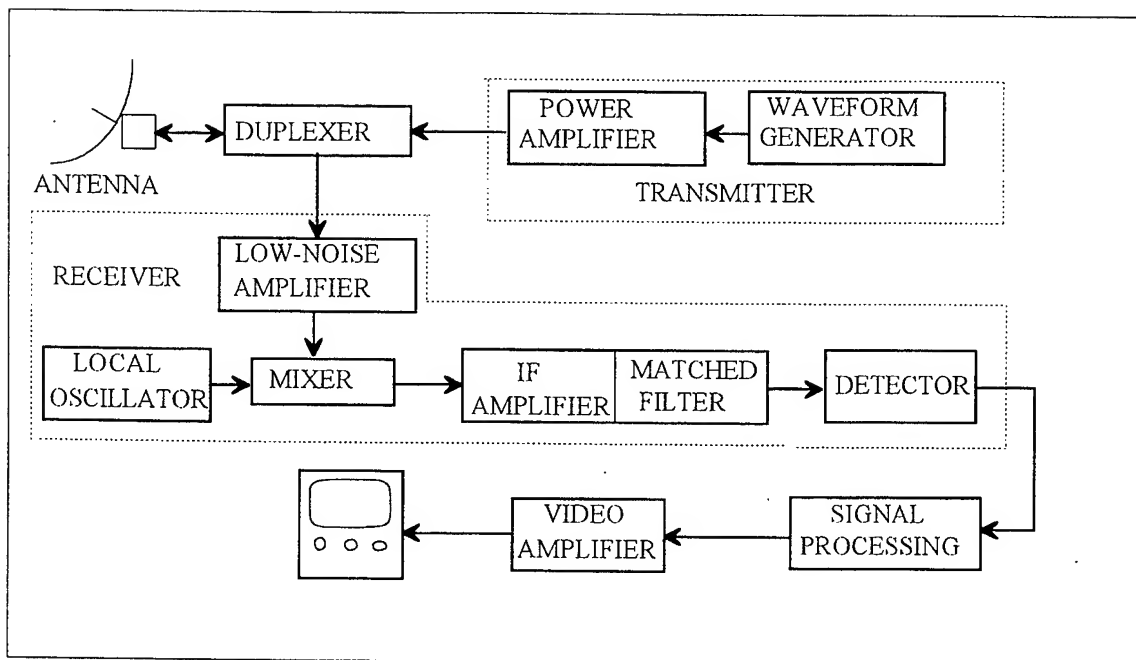
Figure 1.2. Radar system block diagram. [After Ref. 2]

1. Transmitter

The transmitter may include the exciter and driver amplifiers (such as klystron, traveling-wave tube, cross-field amplifier or solid-state device), or a self-excited oscillator (such as the magnetron), the power supply, the modulator, cooling for the tube, heat exchanger for the cooling medium, protection devices for arc discharges, safety interlocks, monitoring devices, isolators, and X-ray shielding. The major component of the transmitter which characterizes the type of the entire radar system is the self-excited oscillator. This is obtained by a combination of a low power stable oscillator and one or more driver amplifier stages (See Figure 1.3 for examples of self-excited oscillator and power amplifiers).

The first successful radars developed prior to World War II, employed a self exited oscillator; the grid-controlled (triode or tetrode) vacuum tube operating at VHF. The magnetron oscillator type transmitter was invented in 1939 and further developed in World War II. It uses the properties of electron streams in crossed electric and magnetic

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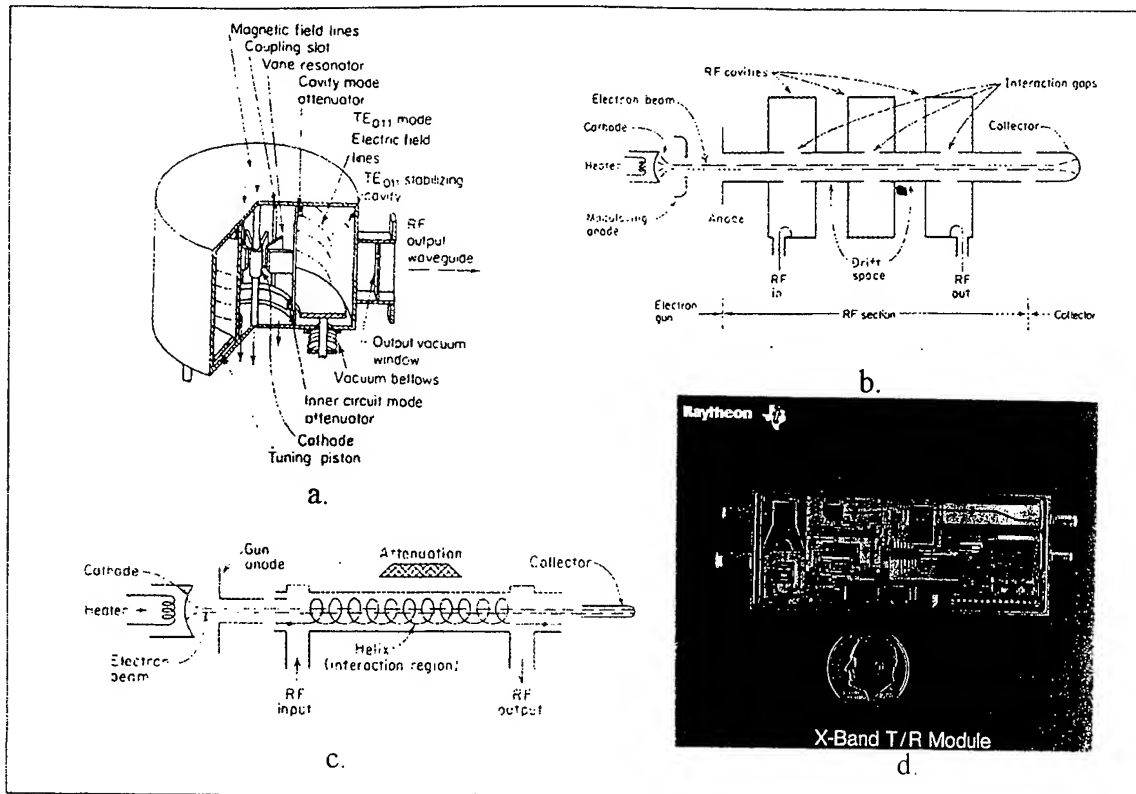
Figure 1.3. (a) Coaxial magnetron with tuning piston. (b) Diagrammatic representation of a three-cavity klystron. (c) Diagrammatic representation of the traveling-wave tube. (d) Transmitter/Receiver module (solid state).|After Ref. 2 and 3]

fields Although several similar devices were realized years before 1939, the application of cavity resonators made the magnetron a workable microwave oscillator. Because it is of small size, weight and cost, and because it does not generate dangerous X-rays, the magnetron tube has been the most widely used self exited oscillator in radar systems even though it is only capable of several kilowatts average power. This output power limits the maximum detection range of the radar. However the simplicity and the small size, gave to the magnetron a big advantage over other competitive devices.

A later improvement in the 1950's was a second type of transmitter, the klystron linear beam tube amplifier. It offered a system of higher power and frequency stability which permitted the use of complex waveforms. Transmitters that employ klystron

amplifiers are of larger size and require more electronic and personnel protection devices so they are limited to use in large non-portable systems.

More recently in the 60's the Traveling-Wave Tube (TWT) linear beam tube amplifier was developed. It has similar properties to the klystron. Its advantage over the klystron however is the wider bandwidth (necessary for good range-resolution) and its disadvantage is the smaller gain. Also the protection requirements are similar to those of the klystron, but more difficult to achieve. Large bandwidth and high power are competing properties of the traveling-wave tube. Usually if we need higher power we must sacrifice some bandwidth. The TWT is used not only as the power tube for high-power radar systems, but also as driver for high power tubes (such as crossed-field amplifiers).

Another amplifier type is the crossed-field amplifier. It is of the same general family as the magnetron. It has small size and weight, high efficiency, wide bandwidth and operates at more convenient voltages than that of the klystron and the traveling-wave tube. Due to the relatively low gain though, it requires more than one stage. The cross-field amplifier utilizes the properties of electron streams in crossed electric and magnetic fields similar to the magnetron.

Presently the use of solid state devices, such as transistors and microwave diode generators is expanding as a result of their rapidly increasing output power level, their reliability, frequency stability and their capability of providing more complex waveforms. Their properties are much different than those of the microwave tubes. Generally they are more compact in size, and of very low weight.

The power of radar transmitters vary from milliwatts for short range radars to several megawatts for over the horizon radars.[Ref. 1,2 and 3]

2. Duplexer

The duplexer, generally a gas-discharge device, is actually a rapid switch which directs energy to the proper path, protecting the receiver from damage when the transmitter is on, or directing weak received echoes to the receiver. The dulexer may be

used with solid-state receiver protectors and/or solid-state circulator for further isolation between transmitter and receiver.

3. Antenna

The antenna is the device that actually radiates the radio waves into space (Figure 1.4). Most often it is a mechanically steered parabolic reflector, or a mechanically and/or electronically steered planar phased array. Antennas achieve narrow directive beams in azimuth and/or elevation concentrating the energy to a possible target and sensing it's angular location. Typical beamwidth for detection or tracking of aircraft is about 1^0 or 2^0. The size of the antenna depends on its frequency, the location, use and environment of the radar. The lower the frequency used, the larger the dimensions of the antenna must be, but tolerances are larger since they are proportional to wavelength.

4. Receiver

The superheterodyne is the type of receiver most often used in radars because we need to lower the frequency of the received signal to be processed. Its main tasks are to separate the desired signal from noise and other signals, and to amplify this signal sufficiently so it can be used in automatic processing devices or displayed to the operator. There is not a general agreement as to where the receiver part stops and the signal processing part begins. Receiver designs vary significantly among different Radar applications.

5. Display

The display is usually a cathode-ray tube with a PPI format (Plan Position Indicator); it provides a map-like presentation with location information in polar coordinates. It might be a computer monitor type display also. While display advances improve human-machine interface, they do not necessarily improve the actual radar performance.

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6. Radar Control

Radar systems usually have the ability to operate at different frequencies within the same band, with different PRI (Pulse Repetition Interval), different waveforms, signal processing and other characteristics. These may change manually by the operator, and/or by a preset program in a computer, according to predicted environment/task combinations.

7. Radar Frequencies

There are no specific limits to the frequencies used by Radar systems. Radars have been operated at frequencies varying from a few megahertz to the ultraviolet region of the spectrum (approximately a thousand THz) [Ref. 2:p. 1.14]. The principles are independent of frequency but practical implementations vary considerably. Each frequency band has its own characteristics that makes it suitable for certain applications and unsuitable for others. Generally radars operating at lower frequencies require larger antennas (not good for tracking), become more affected by ambient noise, require cheaper transmitters, and can operate with larger maximum ranges (electromagnetic waves at HF band may travel over the horizon). Radars operating at higher frequencies may have smaller antennas, but signals become very attenuated by earth's atmosphere and require expensive transmitters which at very high frequencies may not be able to generate large enough power. The extremes of the spectrum are used for special applications while the majority of radar systems operate in the microwave region. Table 1.1 shows the band designations and theoretical limits (in reality there are not sharp borders) as officially accepted by the Institute of Electrical and Electronics Engineers (IEEE), and the specific frequency bands for radar use assigned by the International Telecommunications Union (ITU).

Band Designation	Nominal Frequency Range	Specific Frequency Ranges (ITU)	Use of the frequency band.
HF	3 - 30 MHz		First operational radars.
VHF	30 - 300 MHz	138 – 144 MHz	Early radars (1930). Not many applications.
		216 - 225 MHz	
UHF	300 - 1000 MHz	420 - 450 MHz	Suitable for Airborne Early Warning radars (AEW).
		890 - 942 MHz	
L	1000 - 2000 MHz	1215 - 1400 MHz	Land based long range ARSR.
S	2000 - 4000 MHz	2300 - 2500 MHz	Used for ASR and AWACS.
		2700 - 3700 MHz	
C	4000 - 8000 MHz	5250 - 5925 MHz	Multifunction air defense and medium-range weather radars.
X	8000 - 12000 MHz	8500 - 10680 MHz	Military weapon control, weather avoidance, Doppler navigation.
Ku	12.0 - 18 GHz	13.4 - 14.0 GHz	For Airport surface detection radar. Not many applications in this band. Warhead terminal guidance
		15.7 - 17.7 GHz	
K	18 - 27 GHz	24.05 - 24.25 GHz	
Ka	27 - 40 GHz	33.4 - 36.0 GHz	
V	40 - 75 GHz	59 - 64 GHz	Warhead terminal guidance
W	75 - 110 GHz	76 - 81 GHz	
		92 - 100 GHz	
mm	110 - 300 GHz	126 - 142 GHz	For automotive collision avoidance systems. Research for many short-range applications.
		144 - 149 GHz	
		231 - 235 GHz	
		238 - 248 GHz	

Table 1.1. Frequency bands and their use. [From Ref. 2]

II. NAVY RADAR REQUIRED CHARACTERISTICS

Looking at the published papers in radar area, we can not avoid concluding that most of the ongoing research, is about microwave power modules and phased array antennas. Following this, a reasonable assumption would be that also in the classified area a lot of research effort is dedicated to similar subjects. The reason of course, is the great potential for cost and performance improvement due to advances in VLSI. In order to evaluate this potential and to examine how other system configurations would be lacking without these two components, we first need to examine the possible performance level needed for a navy's multi-function radar (assuming it will operate at S and X frequency band), and afterwards the available components to achieve it.

A. DESIRED NAVY RADAR CAPABILITIES

It is desirable for a midsize ship operating in confined waters to have a multifunction radar with the following capabilities: maximum detection range of 40 miles for surface targets, and 100 miles for airborne targets; ability to determine the targets 3D location and speed (even under clutter), having good multiple target resolution and target identification capabilities; and finally the ability for multiple target tracking, weapon guidance and control. In addition, there is a great need for resistance to Electronic CounterMeasures (ECM). Reliability and graceful degradation is also an important consideration in military applications. In addition consideration of size and cost has to be examined.

1. Detection Range

From the basic radar equation as given in Chapter I page 2, we know that to achieve large detection range we need to have high transmitted power, low frequency, low system noise and high antenna gain. For an aircraft or a missile the approximate Radar

Cross Section (RCS) is very small (for fighter aircraft is approximately 2 m^2 and for a winged missile is about 0.4m^2 [Ref. 3:p 44]). Assuming operating frequency 2 GHz (S band), temperature 290 °K, 5dB signal to noise ratio, 5dB noise figure, 200 MHz receiver bandwidth and 40 dB antenna gain, we can calculate the power needed to detect a small aircraft at 80 nautical miles solving the radar equation for P_t.

$$P_t = \frac{R_{max}^4 (4\pi)^3 kT_o B_n F_n (S/N)}{G_t^2 \lambda^2 \sigma} \qquad (2.1)$$

The resulting power required is 2.15 MW. The above assumed values are normal and achievable with present technology (for the antenna gain I assumed that a phased array antenna is used [Ref. 4]).

Although the detection range requirement for surface targets is only 30 nautical miles, the above calculated power will not guarantee it because of sea clutter. For detection under heavy clutter, power increase is not the solution since this will cause increase of both target and clutter echo. Narrowing the beamwidth and shortening pulse duration will result in smaller resolution cells so target echo will need to compete with clutter return from a smaller area. This along with proper signal processing will help target detectability.

It is worth pointing out that such maximum detection range (approximately 30 nmi) is needed even when the surface target is as small as a fast patrol boat, since today many ships of this size are equipped with guided missiles that have very long range and represent a significant threat. Using the empirical formula 2.2 [Ref. 2:p. 11.17] for the RCS of a naval ship, and knowing that such vessels have an approximate displacement of 300 tons we can approximate their RCS as a function of frequency:

$$\sigma = 52\ f^{1/2} D^{3/2} \qquad (2.2)$$

where: f   = radar frequency, MHz

D   = target full-load displacement, kilotons

Assuming operating frequency of 2 GHz (S band), a minimum RCS of interest for surface targets of the small patrol boat type, would be 382 m². Equation 2.3 [Ref. 2:p. 1.10] provides a way of approximating the signal over clutter ratio which may be substituted for signal-to-noise ratio in the radar equation, since receiver noise power will be much smaller than clutter power.

$$\frac{S}{C} = \frac{\sigma}{\sigma^{\circ} R \theta_b (c\tau/2)\sec(\phi)} \qquad (2.3)$$

where: σ° = normalized clutter coefficient

σ = radar cross section, m²

R   = range to clutter patch, m

θ_b = azimuth beamwidth, rad

c   = velocity of propagation, m/sec

τ = pulse width, sec

ϕ = grazing angle, rad

Although sea clutter depends very much on weather and σ° is rather unpredictable, a value of -30dB is realistic for low grazing angles according to predictions and experiments [Ref. 2:p 13.13]. Assuming 1° azimuth beamwidth, 1m range resolution ($c\tau/2=1$), and small grazing angle ($\sec(\phi)=1$), the resulting S/C ratio for a range of 30 nautical miles is 25.95dB. Comparing this value with the previously assumed minimum SNR (5dB), we see that for such surface target, the signal-to-clutter ratio is much larger. This indicates that our targets of interest will be most probably detected.

Since the receiver bandwidth is hidden in the minimum detectable signal expression, which is inversely proportional to pulse duration τ, it is understandable that use of longer pulses will increase R_{max}. Although antenna beamwidth does not appear explicitly, it affects R_{max} at least when strong clutter is present.

To summarize, decrease of transmitted frequency and system noise, and increase of transmitted power, pulse duration and antenna gain will increase the maximum detectable range of a radar system.

2. Target 3D Location Determination - Multiple Target Resolution

In today's combat environment at sea, the knowledge of the simple existence of a target is not enough. For military applications its position in 3D space is of great importance also. Radars provide targets location by means of range from the radar, and angular location (azimuth and elevation angles). In order to have range information along with resolution good enough to resolve closely spaced targets we need to transmit as short a pulse as possible. The radar's range resolution R_d can be calculated using equation 2.4 [Ref. 3].

$$R_d = \frac{c\tau}{2} \qquad (2.4)$$

where: R_d = range resolution, m

     c   = speed of light in free space, m/sec

     τ = pulse duration, sec

Short transmit pulses demand wide bandwidth in the receivers which is expensive to have especially in high power signals. An alternative is to shorten the received pulse "artificially" using pulse compression techniques.

Pulse repetition frequency (PRF) plays an important role in radar ranging. High PRF results in short interpulse periods which may cause range ambiguities. In other words if the two way time of travel is larger than the interpulse period, the received signal could be assumed to be the echo of the last transmitted pulse although in reality it is not. Signal processing of received signals using different PRFs can solve such ambiguities.

In order to have the 3D location of the target we need to scan in azimuth and elevation. Knowing which direction the antenna is pointing when it receives an echo, one

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would determine the angular location of the target. The radar angular resolution is inversely proportional to antenna beamwidth in azimuth and elevation respectively (some times these two are not the same for search radars). An approximate relationship between directivity and antenna beamwidth is given in Equation 2.5 [Ref. 2:p. 6.4].

$$G_D = \frac{40,000}{B_{az}B_{el}}$$ (2.5)

where: G_D = Directivity = maximum power density/total power radiated (46dB for 1°

        by 1° pencil beam)

    B_{az} = Beamwidth in azimuth [deg]

    B_{el} = Beamwidth in elevation [deg]

The beamwidth is related mainly to the transmitted frequency and the antennas shape and size. The directive gain (or directivity) is given by Equation 2.6 [Ref. 2:p. 1.7].

$$G_D = \frac{4\pi A_e}{\lambda^2}$$ (2.6)

where: A_e = effective aperture or capture area of the antenna.

From Equations 2.5 and 2.6 we see that beamwidth is inversely proportional to the square of the transmitted frequency, and proportional to the effective aperture ($A_e = \rho_\alpha A$, where A is the aperture area, and ρ_α is the aperture efficiency, typically 60%). High sidelobes are definitely something we need to avoid by choosing the proper antenna configuration and special amplitude distribution across the aperture. Unfortunately by lowering sidelobes we increase the beamwidth, so compromise is needed.

We conclude that, to improve a radar's ability to accurately determine the 3D location of the target we need to increase range and angular resolution. In order to improve the range resolution and avoid ambiguities we should do at least one of the following: decrease pulse duration and PRF, use pulse compression, use different PRFs to be able to solve ambiguities. In order to improve angular resolution we should increase the

transmitted frequency and/or the antenna effective aperture, while making the optimum compromise between sidelobes and beamwidth.

3. Clutter Rejection

Our system should have the means to reject clutter (Moving-Target Indicator) in order to be able to detect targets moving with speeds varying from 5 knots to approximately Mach 4, because a ship might move as slow as 5 knots, or a missile might fly as fast as Mach 4 while an island is in the background of our radar beam, causing severe clutter for low elevation targets. Low Pulse Repetition Frequency (LPRF) makes clutter rejection very difficult since clutter's echo spreads and overlap in frequency domain covering the whole spectrum. High Pulse Repetition Frequency (HPRF) eases the detection of high speed targets since the clutter-free spectrum region is the widest. Low speed targets might fall in the clutter region even when HPRF is used. Although the clutter in MPRF covers wider area (in frequency domain) than in HPRF, it is smaller in amplitude due to reduced overlap of echo in time domain. Thus Medium Repetition Frequency (MPRF) is more appropriate for low speed targets.

4. Velocity Measurement

Velocity is the third parameter we need to know about a target. In our case speed measurement is more important for the faster targets which are usually airplanes or missiles. After all, there should be no harm if we more leisurely deduce the speed of a slow target using the changes in its track. The best way to have a fast velocity measurement is to use a coherent radar capable of Doppler processing to actually measure the range rate of change (radial velocity). The higher the PRF the more data we get about the target, so we can accurately determine its velocity. By increasing the PRF, we also increase the Maximum Unambiguous Doppler (MUD) according to Equation (2.7) [Ref. 1].

$$MUD = PRF - \left(\frac{2V_R}{\lambda}\right) \qquad (2.7)$$

where: V_R = Radar platform velocity, m/sec

       λ = Wavelength, m

However computational demands increases with the increase in PRF, so we need a faster computer and larger memory to process the data. The speed of the fastest expected target along with transmitted frequency will help determine the needed level of PRF. Of course PRF affects other radar characteristics, so it should be adjustable.

5. Target Classification / Identification

It is well known that in any ship's Combat Information Center (CIC) no action can be taken unless a target's location and classification or identification is determined. Radars can enable operators to do non-cooperative target identification if they meet certain specifications. Such specifications might be very short pulse duration and/or pulse compression to be able to get a profile of the target's shape (projection of the main scatterers in the direction of propagation) [Ref. 5 and 6]. Specifically, the range resolution is directly related to pulse length according to equation 2.4. We may also use inverse synthetic aperture radar (ISAR) to obtain a high resolution image in range and in a direction parallel to target motion (2D) [Ref. 5]. Rotating the polarization of the transmitted energy and checking the variation of the echo can also provide enough information to classify or maybe specifically identify a target.

6. Multiple Target Tracking

A navy ship can quite possibly be simultaneously attacked by more than one platform (aircrafts, missiles, other ships). Therefore it should have the means to track several targets and decide on the priority of actions to be taken. To succeed in such mission, a radar should be able to track while scan, rapidly switching between a search and a track mode. This requires the system to be able to form very narrow beams directed to specific angles with minimum delay and/or monopulse angle measurement.

7. Resistance To E.C.M

Electronic Counter Measures (ECM) have become very effective, following most of the advances of radars. We need our radar to be desensitized to such threats. Resistance to ECM can be improved using multiple PRFs, frequency jittering and varying modulation codes in a random manner. Such methods, require additional hardware to provide the signal processing techniques, and consume time. In order to keep power losses at low levels we need to process the signal before amplification, but this increases the need for very low noise figure at these stages. Also a trade off should be made between resistance to ECM and maximum detection range since most of the methods require time sharing of the time-on-target for the various modes.

8. Reliability, Graceful Degradation

In military applications we need to know as precisely as possible the condition and the capabilities of our equipment. Most of the malfunctions might lead to human life sacrifices without fulfilling the mission. A radar with very large maximum detectable range is useless if the false alarm rate is 60%, or if the transmitter gets easily overheated. In addition, a slow and measurable system degradation is preferred (instead of a sudden shut down) to allow repairs to be made before serious problems occurr.

9. Size-Cost

Finally of course, any system has to have limited dimensions and weight to fit on a certain vessel and leave room for other necessary equipment. Cost is also a prime consideration.

B. OUTLINE OF SYSTEM CHARACTERISTICS

Any shipboard radar system needs in general to have all or some of the following capabilities:

- To provide **high power modulated R.F energy** to achieve long range detection.

- To switch transmitted **frequencies from S to X band** in order to enhance system performance in long range surveillance, tracking and weapon control mode.

- To **shift the transmitted frequency** in a random pattern to increase resistance to jamming.

- To do **Doppler processing** (coherent receiver), using hardware filters and DFT algorithms, since this has been proven to be the best way to reject ground clutter and have good discrimination of moving targets, provided that proper weighting of the data is applied before the DFT processing. Use of fast Analog to Digital (A/D) converters is a major consideration and limitation in this area.

- To use **pulse compression** to achieve equivalent pulse lengths vary from 0.01μsec to provide range resolution of 1.5m (according to equation 2.4), good for target classification/identification, while the true length of their **longer transmitted pulses** (when switched to surveillance mode), is longer than 1μsec to improve long range detection.

- To use **variable PRFs** in medium and high PRF modes to avoid range or velocity ambiguities, according to system needs.

- To use an antenna or group of antennas, capable of **hemispherical coverage** even in rough seas, with low sidelobes (depending on the mode).

- To have an antenna capable of providing **adjustable beam patterns**. We might need wide beam when scanning at low elevation angles (close to sea surface), to increase time on target where detection is difficult, and narrower beam when scanning at high elevation angles where clutter is much smaller.

- To have an antenna capable of providing **multiple pencil beams** at precise angular locations for multiple target tracking and/or weapon guidance. Such beams should be able to illuminate the tracked targets from time to time, interrupting but without significally degrading the scanning operation.

- The system should be **very reliable** even under adverse conditions. Therefore a radar that is unaffected by external radiation, shock, and heat is needed in order to stay operational in rough weather and possibly after a near by explosion. In addition, the system should have a low malfunction and false alarm rate.

The phased array type of radar and antenna system is one that goes far in meeting all of these diverse requirements. We will examine the effect of newly developed microwave components on the performance and design of phased array antenna systems.

III. PHASED ARRAY RADAR

Today the only way to fulfill all requirements described in Chapter II is to use a system that utilizes a phased array antenna. Although we have several design choices depending on our application needs, i.e. long range surveillance Radar or a tracking Radar, the multi-function capability can only by achieved by a phased array system. This is a well known fact but in the past, construction of such systems was very difficult. Recent advances in solid state microwave technology and monolithic circuits enabled the radar system designers to more easily apply these concepts to modern phased array systems.

A. PHASED ARRAY ANTENNA

Phased array is a directive antenna made up of individual radiating antennas. It generates a radiation pattern with shape and direction determined by the relative phases and amplitudes of the currents at the individual elements [Ref. 3:p. 278]; this beam can be steered by varying these phases (Figure 3.1). Assuming we need the beam at a direction angle θ_0, we should apply a phase difference ϕ between adjacent elements, where ϕ is given from Equation 3.1 [Ref. 3:p. 282].
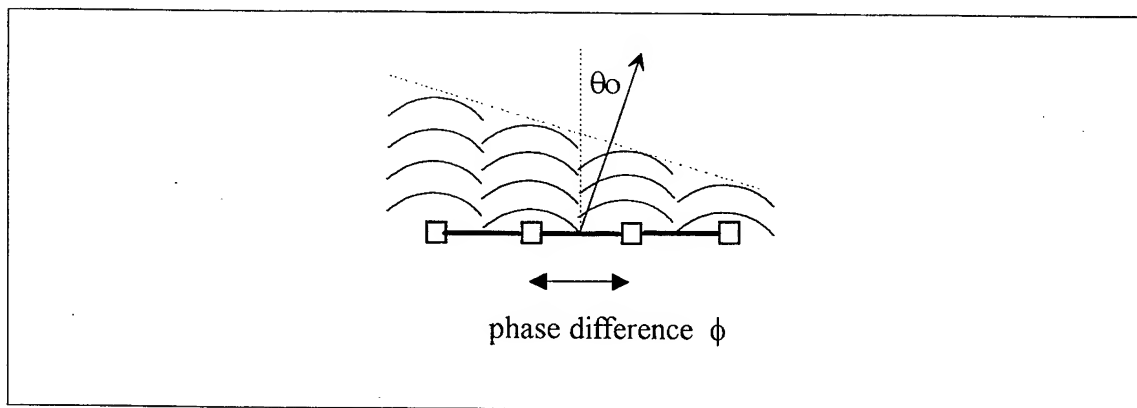
Figure 3.1. Linear array of four elements radiating at an angle θ_o.

$$\phi = 2\pi \frac{d}{\lambda} \sin(\theta_0) \qquad\qquad (3.1)$$

where: ϕ = phase difference between two adjacent elements in a line array [rad]

d = distance between two adjacent elements [m]

λ = wavelength of transmitted signal [m]

θ_o = angle to which the beam will be steered [deg] (relative to the normal of the array)

The radiating elements can, for example, be dipoles, open-ended waveguides, slots in a waveguide or printed-circuit patches. Such antennas, were known from the first decades of the twentieth century. They were used on early radar systems, but as the employed wavelengths became shorter, parabolic reflectors, being simpler and cheaper, displaced the array antennas which were much more complicated. In World War II, United States, Great Britain and Germany, used radar with fixed phased-array antennas, in which mechanically actuated phase shifters were used to steer the beam. From the early 1950s, the mechanical actuated phase shifters were replaced by electronic ones. Frequency scanning was the first and the most applied method. Later on, the Huggins phase shifter came up (based on the same principles as the frequency scanning but with the benefit of keeping the same radiated frequency). Recently, digitally switched phase shifters which employ either ferrites or diodes (introduced in 1960s), are applied in phased arrays that can steer the beam in two orthogonal angular coordinates. Since today's radar system engineers have to meet very demanding specifications, more attention is directed to array antennas and research results are already very promising.

Using these antennas we gain the capability of switching beams rapidly and accurately, a fact that allows multiple radar functions to be performed almost simultaneously. In addition, the redundancy that a multifunction radar can provide to a military unit is significant. An electronically steered phased array radar may track a great multiplicity of targets, illuminate a number of targets with RF energy to guide missiles towards them and perform hemispherical search with automatic target selection. It may

even act as a communication system with distant receivers and transmitters [Ref. 2:p. 7.1]. Therefore it can substitute in an emergency for any other system dedicated to one of the above functions.

The beam of an array antenna can be electronically steered using several methods. The beam points in a direction normal to the phase front; therefore to control the beam we need to control the phase of the elements. This can be done by varying, the feed line length, permeability, dielectric constant using phase shifters which can be adjusted to a value 0 to 2π rad, or the velocity of propagation in the feed line. Also, if we vary the transmitted frequency, the relative phase of the elements in an array changes and the outcome is beam steering. This is frequency scanning or steering. The last method is the easiest to implement and has been used widely in the past. On the other hand, it is not the preferred approach since this method requires that a considerable part of the usable signal spectrum must be reserved for beam steering, therefore it can not be used for extraction of further target information.

B. MODULAR SYSTEM DESIGN

It is obvious that different signal processing is needed for each element or group of elements (where frequency scanning is not employed). Such processing can more easily be done at low power signals which later are amplified to be transmitted at proper power level. If we apply this amplification as close to the radiating elements as possible, the power loss is smaller and the system becomes more efficient. The different signal processing and the power amplification can be accomplished by the use of a separate module for each element. Each of these modules can be placed directly behind the radiating element so transmission loses are minimized.

There are two major groups of modules available today. The Solid State Modules (SSM) and the Microwave Power Modules (MPM). The first has already been used in numerous systems while the second, since it has been very recently developed, has not been used yet in a radar system. In order to study the advantages and disadvantages of

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these module designs compared to each other and to the older TWT design, we need first to look further into the description and main characteristics of the Solid State and the Microwave Power modules.

1. Solid State Modules

a. General Description

Space, power and money are saved by the use of dual path modules (Figure 3.2); the transmit/receive (T/R) module uses one phase shifter for both transmit and receive function. The fundamental functions of the T/R module are to provide gain and power output in the transmit mode, to provide gain and low-noise figure in the receive mode, to switch from transmit to receive mode and vise-versa when this is appropriate, and finally to provide phase shift in both modes for beam steering [Ref. 2:p. 5.16].
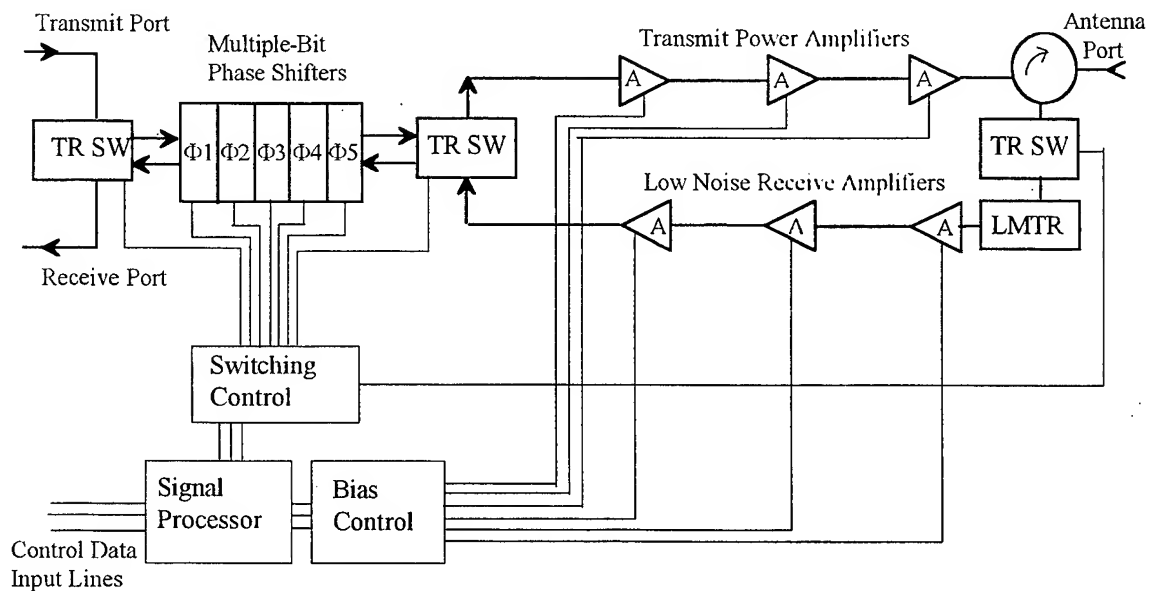
Figure 3.2. Block diagram of a generic dual path transmit/receive module for phased array radar. [After Ref. 2:p. 5.17]

The recent use of Microwave Monolithic Integrated Circuits (MMIC) has enabled module configurations of much higher performance and smaller size, since more and more complex functions can be realized using MMIC technology. New system architectures that were difficult or impossible to construct with older technologies, can now be used in real systems. The MMIC includes active and passive devices formed on a semi-insulating semiconductor substrate, usually GaAs.

The advantages of MMIC design approach are:

- **Low-cost circuitry**. Component assembly is reduced to a minimum since most of the module devices (active and passive) are on the same substrate. Batch processing reduces the circuitry cost also.

- **Increased reliability**. Reduced number of parts and connections lead to an increased reliability.

- **Small size and weight**. Integration of many components onto one chip results in high density circuitry, not achievable when connected discrete components are used.

There are still however some disadvantages mostly due to the high cost of wafer processing, along with the non-recurring engineering design requirements. If application fields become broader, mass production could alleviate these problems. Another disadvantage is the inability to fine tune circuits to achieve peak performance. This is difficult to accommodate in the MMIC approach. Since some processing variations will always be present, limited trimming demands acceptance of lower specification goals for a given design [Ref. 2:p. 5.17].

b. Transmitter/Receiver Module Performance Characteristics

The partitioning of T/R module circuit functions onto GaAs chips demands a tradeoff among several design issues. The resultant circuit represents a compromise among the goals of optimum RF performance. Performance characteristics of monolithic circuits vary significantly as a result of processing variations, layout considerations, optimization or circuit complexity [Ref. 2:p. 5.18]. In order to see and understand the advantages and disadvantages of the use of solid-state modules compared to other design approaches for our system of interest (multifunction naval radar), we need to look into

representative design characteristics of the major building blocks of such modules. This will enable us to see the technical difficulties that we need to overcome in order to achieve the desirable performance which makes the solid-state design competitive or superior to older design approaches.

Design criteria/characteristics for **low-noise amplifiers** are:

- The **actual size** of the device is very important in multiple-stage designs. The package and the transmission lines introduce parasitic capacitances altering the impedance of the device. Variation of the size and length of the transmission line affect the impedance of the components and increases the intermodulation distortion product.

- Since circuit losses on the input degrade the noise figure, utilization of **off-chip matching** will be helpful.

- A low noise-figure requires **bias close to the pinch-off voltage of the Field Effect Transistors (FET)** used. In such case, gain and noise figure are highly dependent on the pinch-off voltage. Since the pinch-off voltage can vary significantly even for devices from the same wafer, the bias condition should be chosen carefully. Gain and noise figure are traded off against repeatable performance. Combination biasing can provide high gain and repeatable performance but this will increase the noise figure (see Appendix).

Design criteria/characteristics for **power amplifiers**:

- Total gate periphery is at a premium. For high-power design, the **load impedance** presented to the final device must be chosen carefully to maximize power output and efficiency.

- **Off-chip matching** is needed to reduce loses in the output circuit of the final stage in order to maximize power output.

- GaAs is a poor thermal conductor. Adequate **heat sinking** of the chip is mandatory.

- In order to increase efficiency of multiple-stage designs, the **final amplifier stage should reach saturation before the preceding stages**.

Design criteria/characteristics for **transmit/receive switching**:

- The **ratio of OFF-ON resistance** of the FET should be kept as high as possible. The channel length largely determines the ON resistance. The tradeoff between short gate length (lower processing) and insertion loss must be examined. It is easier to construct long gate length devices but increased gate length will increase insertion losses.

- In critical applications, usually the front-end switching configurations in a T/R module (before the receive low-noise amplifier or after the transmit amplifier), the **FETs geometry** is very important. The parasitic drain-source capacitance which affects the OFF-state isolation of the device depends largely on the source-drain spacing. If we need our device to operate at higher frequencies we should increase the source-drain distance to reduce the parasitic capacitance. This will reduce the source-drain leakage and OFF-ON resistance ratio will be kept high even in high frequencies.

Diode Phase-shifter designs can utilize a switched-line, a hybrid-coupled, or a loaded-line circuit configuration [Ref. 2:p. 7.63]. Distributed transmission-line components or lumped-element equivalent circuits are used to achieve the needed multiple-bit phase shifting.

- **Switched-line** configurations rely on FET switches to switch lengths of transmission line. They are typically used for higher frequencies where less chip area is needed [Ref 2:p 5.19]. They are restricted to true-time delay switches and to low power miniaturized phase-shifters where losses are not the major consideration. The theoretical peak power capability is twice that of the hybrid-coupled. Although the insertion loss does not vary with the amount of phase-shift, it is quite large and it further increases if we need to improve the phase-frequency response [Ref. 2:p 7.63].

- **Hybrid-coupled** phase-shifters use a microwave hybrid to change the distance at which a reflection takes place to achieve phase shift. They have less power loss, use the least number of diodes, operate over wide band of frequencies but can handle the least peak power (maximum 1KW).

- The **loaded-line** technique is used where higher peak power and smaller phase increments are desired. In this configuration diodes are used to switch increments of capacitance and inductance to provide the small changes in phase. These phase-shifters are large and bulky compared with the other two.

Recently **ferrite phase-shifters** has shown very attractive characteristics (Table 3.2). Using their anisotropic magnetic properties one can change their permeability to achieve the desired phase shift. Recently, reciprocal (dual-mode) ferrite phase-shifters have been built. Since the ferrite phase-shift mechanism is inherently nonreciprocal, this recent advance consists only of the integration of two ferrites in a circuit to achieve phase-shift in the two-way RF path. Ferrite phase shifters are heavier and bulkier than comparable diode devices. On the other hand, they can be very accurately controlled,

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enjoy low losses and can handle up to 100KW peak power. The largest disadvantage of the dual-mode phaser is the slow switching speed (from twelve to hundreds of microseconds).

Typical characteristics of diode phase-shifters are shown in Table 3.1 , and that of the ferrite phase-shifters are in Tables 3.2 and 3.3.

Finally, in order to have an approximate overview of what a solid-state transmit/reseive module has to offer to our system of interest (naval multifunction phased array radar), Table 3.4 is provided. Since amplitude and phase sensitivity (to power supply ripple) have impact on the MTI improvement factor (the ratio S/C at the output, over S/C at the input of the clutter filter) which is very important in radar applications, these sensitivities have also been added to the Table 3.4 [Ref. 2:p. 5.21]. Increased gain sensitivity results in a degraded output pulse fidelity (envelope) even for small variations of the RF drive level. The corresponding limit on MTI improvement factor caused by amplifier amplitude instability is:

$$I = -20\log(\frac{dA}{A}) \qquad (3.2)$$

where I = MTI improvement factor

dA= amplitude ripple, V

A = magnitude of the amplitude, V

Increased phase sensitivity will degrade the MTI improvement factor also. In a multistage amplifier the phase errors of serially cascaded stages are added. The resulting limit on MTI improvement factor is:

$$I = -20\log(d\theta) \qquad (3.3)$$

where $d\theta$ = the magnitude of the insertion phase ripple.

So it is important to keep the gain and phase sensitivity of the transmitter low.

	S band	C band	X band
Insertion Range	1-1.2 dB	2.0 dB max.	3.0 dB max.
VSWR	1.4:1 max.	1.3:1 max.	1.5:1 max.
RF power	50W CW	50W peak	50W peak
Number of bits	6	6	6
Switching time	0.5µs	1.0µs	1.0µs
Size (with connectors)	2.5 x 1.5 x 0.5 in	2.5 x 1.5 x 0.5 in	2.5 x 1.5 x 0.5 in

Table 3.1. Diode phase shifters typical characteristics. [From Ref. 2:p. 7.64]

	phase shift available	RF power (peak/average)	Insertion loss, dB max	Maximum VSWR	phase shift accuracy	Maximum switching time
S band (5% bandwidth)	360° 5 - 8 bits	40KW / 800W	1	1.2:1	2 - 5° rms	20 µs
C band (5% bandwidth)	360° 5 - 8 bits	10KW / 400W	0.8	1.2:1	2 - 5° rms	8 µs
X band (5% bandwidth)	360° 5 - 8 bits	500W / 100W	0.6	1.2:1	2 - 5° rms	3 µs
Ku band (5% bandwidth)	360° 5 - 8 bits	250W / 50W	0.5	1.2:1	2 - 5° rms	2 µs
6.5-18 GHz (5% bandwidth)	360° 4 - 6 bits	5KW / 100W	1.8	1.5:1	6° rms	3 µs
Ka band (5% bandwidth)	360° 4 - 6 bits	50W / 20W	1.2	1.2:1	2 - 5° rms	<2 µs

Table 3.2. Typical characteristics of nonreciprocal Ferrite Phase-Shifters. [From Ref. 2:p. 7.65]

	C band 10% bandwidth	X band 10% bandwidth	Ku band 10% bandwidth
Freq.	1.0 dB	1.0 dB	1.0 dB
VSWR	1.5:1 max.	1.5:1 max.	1.5:1 max.
Rf power	250W peak 10W average	250W peak 10W average	200W peak 10W average
Phase error	4° rms	4° rms	4° rms
Switching time	250μs	150μs	50μs
Weight (with driver)	4oz	1.5oz	0.8oz
Size	0.815 in diameter 4 in length	0.55 in diameter 3 in length	0.34 in diameter 2.5 in length

**Table 3.3.** Typical characteristics of dual-mode reciprocal Ferrite Phase-Shifters. [From Ref. 2:p. 7.67]

TYPICAL PERFORMANCE CHARACTERISTICS									
Freq.	Transmit Mode			Receive Mode					
	RF power W	Gain dB	Efficiency %	Gain dB	Noise figure dB	rms phase error		Size in^3	Weight oz
						Gain (dB)	Phase (deg)		
L band	11	35	30	30	3	0.8	5	4	4
S/X band	2	30	25	...	...	...	...	0.25	N.A
X band	2.5	30	15	22	4	0.6	6	0.7	0.7
PERFORMANCE SENSITIVITIES									
PARAMETER	TRANSMIT			RECEIVE					
Gain Sensitivity to drain voltage	1 dB/V			1 dB/V					
Phase Sensitivity to drain voltage	4°/V			2°/V					

Table 3.4. Integrated transmitter/receiver module performance characteristics and sensitivities. [From Ref. 2:p. 5.20]

2. Microwave Power Module

The MPM combines both solid-state and vacuum electronics technology in a single unit, and leverages the advances of each while minimizing their disadvantages [Ref. 7]. It includes a wideband Monolithic Microwave Integrated Circuit (MMIC) driver, a highly-efficient miniaturized vacuum power booster and integrated power conditioning, in a compact lightweight package (Figure 3.3).
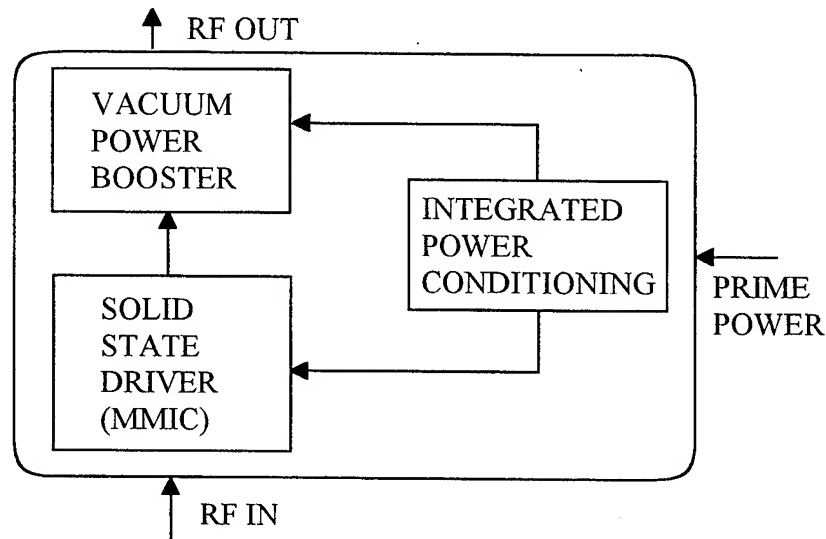
Figure 3.3. The MPM integrates Solid-State and Vacuum electronics. [From Ref. 8].

The MPM can support broadband capability in S, C, X, and Ku band. It can also provide higher sensitivity and resolution than the older designs, through improved stability and reduced noise levels [Ref. 8].

The gain of the MPM is partitioned between the MMIC and the vacuum power booster with approximately 50% split. This arrangement provides the following significant benefits:

- High transmitter efficiency and reduced thermal management problems.

- Broadband power capability, arising from gain partitioning and subsequent gain reduction of the vacuum power booster.

- Transmitter is capable of operating at high ambient temperatures, with temperature compensation incorporated in the MMIC driver.

- Gain compensation, variation, and improved phase-matching/control incorporated in the MMIC amplifier stage.

- Miniature transmitter size and light weight.

- High reliability, arising from reduced high voltages for the vacuum power booster, and the control of the amplifier and power conditioning interfaces.

- Reduced cost by potential high-volume manufacture, with further cost reductions realized through the development of a multi-purpose or standardized MPM serving a variety of needs.

- Flexibility in system architecture. [Ref. 8].

A comparison between vacuum devices, solid state devices and MPM that illustrates the superiority in most aspects and the potential of a more general use of the MPM is shown in Tables 3.5 and 3.6. Specifically for the Table 3.6 the following assumptions are made: a) The Solid State Power Amplifier (SSPA) is composed of 20%-efficient 10 watt modules combined with 90% efficiency, b) the Traveling Wave Tube Amplifier (TWTA) consists of a 40%-efficient TWT an 85%-efficient high-voltage power supply, and c) the MPM is based on a 50%-efficient vacuum power booster and a 90%-efficient power supply. For the cost comparisons estimations are as follows: SSPA modules are $1K each (combiners not included); TWT cost is $5K, the power supply $25K; the vacuum power booster and the MMIC in the MPM are $2.5K each, and the integrated power conditioning and packaging is $5K. Size and weight were estimated from actual amplifiers, and the MPM size and weight is based on the average package resulted from phase I of the MPM program (funded by DOD.) which was initiated in November 1991 and ended in June 1994 [8]. Phase II of this program is still under development at Hughes EDD, Northrop ESD, Litton EDD, Teledyne MEC, Varian TWTP and Westinghouse ESG. Assistance is provided by Army Research Laboratory, Air Force Wright Laboratory and NASA Lewis Research Center while the central program manager is the Naval Research

Laboratory. The MIMIC program was also a great support to the MPM program under phase II of the Raytheon/TI Joint Venture in the "Micro-TWT Driver Module Demonstrator Development" task [Ref. 8].

	VACUUM DEVICES	SOLID STATE DEVICES	MPM
POWER	High peak or average power from single device	Many single low-power devices combine to achieve power	Moderate power device combinable to high power output powers.
EFFICIENCY	Highly sufficient devices	At comparable output power, low efficiency due to combining	Extremely efficient transmitter.
NOISE	Noisy high-gain devices	low noise devices	Favorable noise performance.
SIZE & WEIGHT	Magnetic fields (beam control), high voltages (beam power), and heater supplies (thermionic cathodes) add to size and weight.	No magnetic field or high voltage requirements. Low efficiency requires bulky thermal management systems.	Order of magnitude breakthrough in packaging.
COST	Single device cost high due to labor-intensive manufacturing	High volume microfabrication can lead to low single-device cost	Standardized or modular design leads to low cost.

Table 3.5. Comparison between vacuum devices, solid state devices and MPM. [From Ref. 8]

	EFFICIENCY	PRIME POWER	SIZE/WEIGHT	COST
SSPA	15%	675 W	TBD	$ 20 K
TWTA	30%	333 W	150 in^3,10 lbs	$ 30 K
MPM	45%	225 W	10 in^3, 1 lb	$ 10 K

Table 3.6. Comparison that shows domination of MPM over SSPA and TWT in 100W 6-18 GHz amplifier options. [From Ref. 8]

IV. TECHNOLOGY CAPABILITIES

The advantage of using compact transmit/receive modules in a naval multifunction radar system design over the older design based on vacuum tube amplifiers was described in Chapter III. Although performance trend of MPM has demonstrated a great improvement in microwave power capability during the last few years (as shown in Figure 4.1). It has not as yet reached a power level high enough to be used in our application of interest. The use of the Microwave Power Modules, although not suitable at this time due to power limitations, has an increasing record of power capability that shows it will probably reach power level capabilities meeting our needs within the next 5 years.
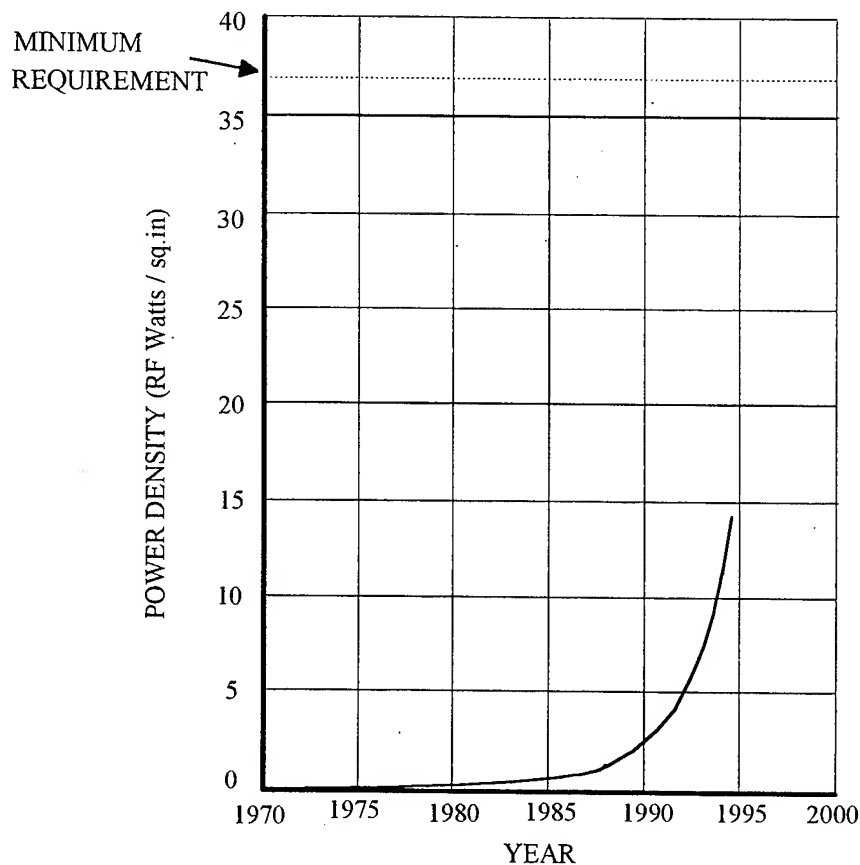
Figure 4.1. MPM power improvement. [After Ref. 8]

There have been manufactured MPMs of power up to 100 W in the frequency range from 6 GHz to 18 GHz, while for our application we need approximately 500 W. On the other hand, solid-state technology is presently mature enough to overcome the difficulties that our demanding application generates.

A. PRESENT SOLID-STATE TECHNOLOGY CAPABILITIES APPLICABLE TO NAVAL MULTIFUNCTION RADAR DESIGN

With present technology, manufacturers can supply power amplifiers with silicon transistors, capable of 500 W output power at 2 GHz. Such an amplifier block will consist of four amplifier base cells. Each base cell will contain two transistor die cells with output power of 60 watt (CW) each. If a 6% duty cycle is used, the output power of the same amplifier block will reach 720 watts. The simplified block diagram of the amplifier block is shown in Figure 4.2. The die cells are the transistors in the "device" part of the diagram. The four distinct amplifier cells are shown in the middle part of the diagram with two transistor in each cell. In Figure 4.3 there is an amplifier block of the same configuration with output power of 30 watt. The gain of such a device will lie between 8 and 10 dB and its efficiency will be approximately 60% ["Spectrian" data sheets] The bandwidth of the amplifier will be approximately 200 MHz. The Low Noise Amplifier in the receiving path of the module can easily have a noise figure of 3 to 4 dB (Figure 4 4) [Ref. 9].

In order to have the multifunction capability, we need the radar to be able to transmit at a frequency approximately 2 GHz in the long range surveillance/tracking mode, and at approximately 6 GHz in the weapon-control mode. It is not possible to use the same solid-state amplifier in both modes since impedances of its components are frequency dependent and load matching for a single amplifier is very difficult to achieve when it is used at two so widely different frequency-range of operation. This problem can be solved however since the size of such an amplifier can be small enough (approximately 6.5x2x1 inch) that it is possible to use two separate amplifier blocks for each transmitting element, one operating at 2 GHz and the other one at approximately 6 GHz. From 1991, it has been
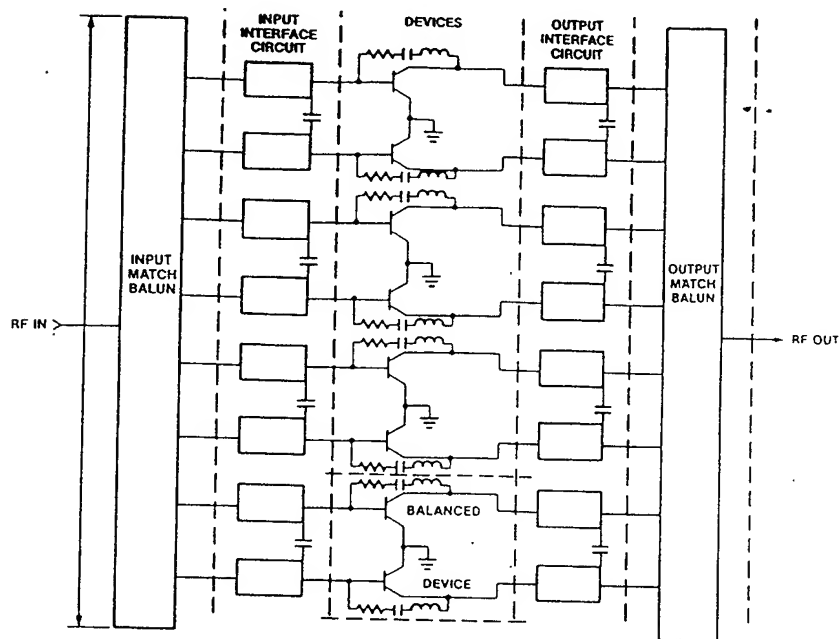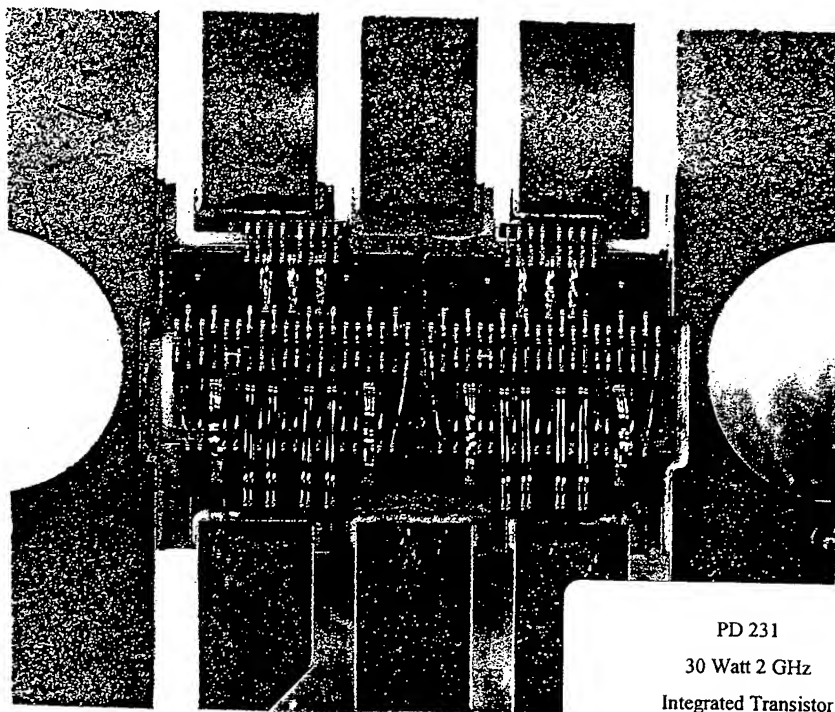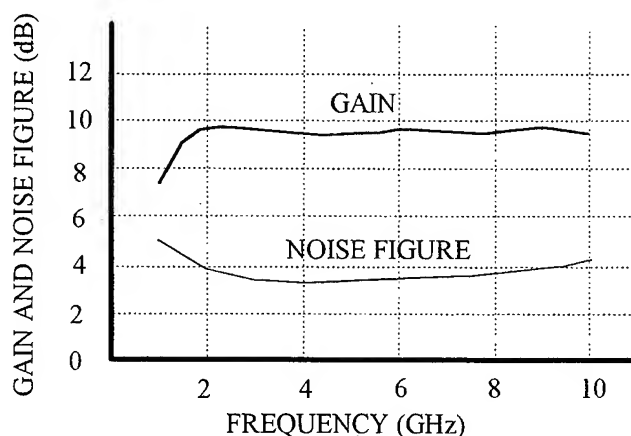
Figure 4.2. Simplified block diagram of the power amplifier.

PD 231

30 Watt 2 GHz

Integrated Transistor

**Figure 4.3**. Power amplifier block with 30 W output power.

Figure 4.4. Gain and noise figure of a distributed GaAs LNA. [After Ref. 9].

possible to build solid state transmit/receive modules (GaAs) with 15 W output power at 6.8 GHz [Ref. 10], and a noise figure of 2 dB. If even higher frequencies, for example 18 GHz is chosen for the high frequency module, InP-based (AlInAs/GaInAs) High Electron Mobility Transistors (HEMTs) can be employed to achieve noise figure as low as 0.5 dB with 16 dB gain (Figure 4.5) [Ref. 11]. The amplifier associated with the high frequency weapon-control function will have lower output power. This however is not a major problem since in the system application we are anticipating that the needed maximum weapon-control distance to be much smaller than the desired maximum detection range. Therefore, these high frequency amplifiers can successfully be used in the same radar system for the weapon-control mode, even though they provide lower output power than the 2 GHz amplifiers associated with the surveilance/tracking mode.

The phase shifter will not limit the module capabilities since we can have 6 bit diode phase shifters that can handle powers up to 1KW with a switching time less than 10μsec [Ref. 2:p. 7.63]. This switching speed will give the radar the ability to track multiple targets without significantly degrading the scanning performance. The 6 bit phase shifter provides enough angle accuracy for our application. It would also be possible however to use 7 or 8 bit phase shifters for better angle precision and lower sidelobes, but
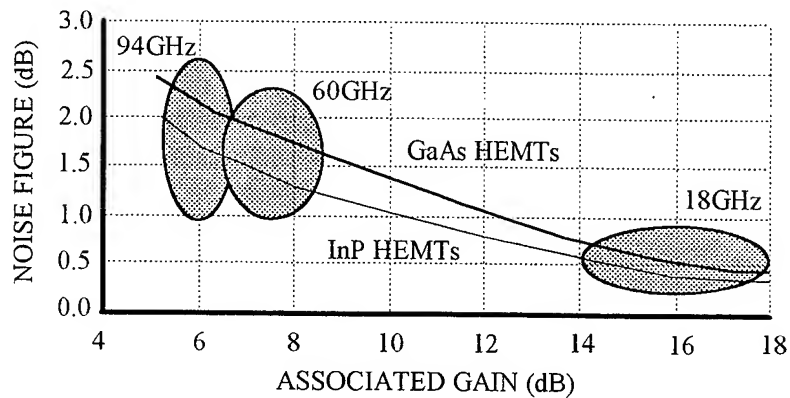
Figure 4.5. Minimum noise figures for GaAs-based and InP-based HEMTs. [After Ref. 11]

this will significantly increase the losses. So although 7 or 8 bit accuracy is available, it is not yet a good choice due to power limitations.

Since we know the device technology capabilities, we need now to translate these achievements into radar characteristics in order to verify that these device specifications coincide with the tactical requirements described in Chapter II. The operational tool for exploring this trade off will be the basic radar range equation.

B. SYSTEM CAPABILITIES "VERIFICATION"

Our system will have four active phased arrays for hemispherical coverage as described in chapter III. Assuming we will use a 4100 element array (following the SPY 1 example) the total radiated power (using the above mentioned modules) will be:

$$P_t = 4100 \times 500 = 1.05MW \qquad (4.1)$$

The noise figure will be 4 dB (F_n=2.512), the bandwidth 200 MHz and the signal to noise ratio 5 dB (SNR=3.162). For the rest of the radar parameter values we will keep the same assumptions as in Chapter III, page 12. Substituting these values into the radar range equation (for clarity, we repeat here Equation 1.1) we get:

$$R_{\max} = \left[\frac{P_t G_t^2 \lambda^2 \sigma}{(4\pi)^3 k T_0 B_n F_n (S_0/N_0)_{\min}}\right]^{1/4} \qquad (1.1)$$

where: P_t = transmitted power, watts

       G_t = antenna gain

       A_e = antenna effective aperture, m^2

       σ = target radar cross section, m^2

       $(S_o/N_o)_{\min}$ = Minimum signal to noise ratio

       F_n = noise figure of receiver

       B_n = receiver bandwidth, Hz

       T_o = 290 °K

       k   = Boltzmann's constant = 1.38×10^{-23} J/deg

where $S_{\min}$ = $k\, T_o\, B_n\, F_n\, (S_o/N_o)_{\min}$ = Minimum detectable signal, watts.

Choosing a radar cross section $\sigma = 2 \ m^2$ for a small fighter airplane:

$$R_{\max} = \frac{1.05 \times 10^9 \times (10^4)^2 \times 0.15^2 \times 2}{(4\pi)^3 \times 1.38 \times 10^{-23} \times 290 \times 200 \times 10^6 \times 2.512 \times 3.162} \qquad (4.2)$$

$$R_{\max} = 164.4 Km = 88.8 nmi \qquad (4.3)$$

And if we use $\sigma = 0.5 \ m^2$ (for missile) we get:

$$R_{\max} = 116.3 Km = 62.8 nmi \qquad (4.4)$$

If on the other hand an amplifier that transmits at 6.8 GHz with an output power of 15W is used in the weapons-control mode, and the noise figure of the receiving path is 2 dB, then a 4100 element array antenna will have an output power of 61.5 KW. Such a system, assuming a radar cross section area of $0.5 m^2$ (missile), can provide guidance / control for a range of 15 nmi.

The 3 dB beamwidth of the phased array, with the elements spaced by λ/2 to avoid sidelobes, can be approximately calculated using the following formula (Equation 4.5 [Ref. 2:p. 7.2]).

$$\theta_B = \frac{100}{\sqrt{N}} \qquad (4.5)$$

where θ_B = 3 dB beamwidth [deg].

N = number of radiating elements for this pencil beam.

Since we have assumed 4100 elements in the array the approximate beamwidth for pencil beam will be 1.56 deg.

The previously stated facts verify, that a solid state multifunction active phased array radar, that meets the general requirements of a medium size ship operating in relatively confined waters (such as the Aegean sea), as stated in Chapter II, can be built with todays technology.

C. SOLID STATE ACTIVE PHASED ARRAY RADAR SYSTEM ADVANTAGES

The advantages of such a system compared to an older tube or solid-state point-source type radar are significant.

1. Comparison Of Solid-State Active Phased Antenna Radar With Tube Type Radar

Solid state modular systems:

- do not need warm-up, so there is not any delay at startup nor wasted heater power. The heated cathodes of the tubes are one of the causes of tube limited operating life that solid-state power modules do not have.

- do not need high voltages, this enables us to avoid large spacing, oil filling or encapsulation. We save space and weight while reliability becomes higher.

- exhibit much improved Mean Time Between Failures (MTBF) compared to tube-type transmitters. Module MTBF in excess of 100,000 hours have been measured.

- do not require separate pulse modulator.

- provide graceful degradation of system performance when they fail. Overall power output in decibels degrades only as $20\log(r)$, where r is the ratio of operating to total number of amplifiers.

- are able to provide 50% or more bandwidth with good efficiency, while high-power microwave tubes can achieve only 10 to 20 %.

- can help in reducing the transmission loses since they can be placed directly behind the radiating element minimizing the distance that the high-power microwave signal has to travel before it is radiated to free space. Tube-type amplifiers are high power point sources, so the microwave signal is generated at a point and then is divided and distributed to the radiating elements, thus transmission loses are inevitable.

- enable the system to perform the signal processing tasks (mainly the phase shifting) at low power. This minimize high-power losses of the phase shifters at the radiating elements and raises the system efficiency.

FEATURE	SSAPAR (New)	VTR (Old)
Mean Time Between failure	100,000 h	10,000h to 40,000h
Graceful Degradation	Yes	No
Needed Voltages	Several Volts	40KV to 90KV
Bandwidth	50%	20%
Transmission Losses	Minimum	High
Warm-up	0 min	15 min

Table 4.1. Comparison summary between Solid State Active Phased Array Radar (SSPAR) and Vacuum Tube Radar (VTR).

The most significant advances in microwave array devices for radar are in the area of the transmit/receive modules. Complex architectures are being realized. A minimal quantity of monolithic microwave integrated circuits are interconnected to realize high power devices. Phase shifters are shared between transmit and receive paths in such a way as to increase dynamic range and reduce parts count. However, although the improvements in compactness and packaging are significant, there is still much to be

understood and improvements to be made in several related technology areas, such as coupling within the module structure, leakage through the package and coupling between RF transfer lines [Ref. 12].

Calibration provides a method of obtaining a high degree of uniformity over a variety of operating conditions and frequencies. New array calibration techniques contribute to better system performance by providing the system with desired sidelobe levels. This is achived without resorting to stringent gain, insertion, and phase matching of individual components and interfaces over the defined frequency band and output power ranges [Ref. 13]. These improvements in calibration enabled engineers to relax some of the unattainable requirements on transmit/receive modules and other array components.

Of course, the detailed design of a transmit/receive module remains a complex task. Power spectral density and purity concerns increase the performance level required from the power conditioning circuits. High output power levels at high efficiency forces the selection of more expensive device technologies while cost considerations drive the design towards higher level of integration to reduce part count and labor expenses.

The higher integration of several thousand microwave components into a tightly packed assembly without losing the ability of systematic testing to verify proper operation is still a challenge. Improvement is always needed and progress is indeed continuous. Microwave device technology however, has already reached a level high enough to provide a radar system that meets the requirements as stated in Chapter III. Module performance levels that have been achieved are fully supportive of the requirements for active phased array radar systems.

V. CONCLUSIONS

It has already been recognized for a number of years that phased array apertures can provide tactical aircraft with enhanced radar system performance [Ref. 13]. Now the improvements in solid state microwave device technology (mainly the ability to deliver higher power) will enable navy ships to use the tactical benefits that an active phased array radar system can provide.

Requirements for future navy tactical ship radars, as described in Chapter II, are very demanding (summary in Table 5.1). Such radar performance can only be achieved by a phased array radar system. Technology, using a conformal phased array tightly integrated with ships frame and radome, is now available to permit building a low radar cross-section antenna. Even if the proposed modules are only capable of low power output, by increasing the number of radiating elements and modules, it is possible to attain remarkably high RF output levels. Therefore even stealthy targets can be detected. Phased arrays can provide beams of various shapes. These RF energy beams can also change direction rapidly and accurately, following different algorithms, depending on the radar task.

Next-Generation Navy Ship Characteristics/Requirements	Dictated Radar Requirements to meet Next Generation Ship Characteristics
Stealth Ship	Low radar cross-section antenna tightly integrated with ships frame and radome.
Engagement with Stealth Targets	Very high radiated RF power, much reduced RF losses.
Simultaneous Multiple Target Engagement	Multiple target track, multiple missile guidance over wide field of regard with high revisit rates.
Reduced ECM Susceptibility	Ultra-low receive sidelobes on sum and both monopulse patterns, very wide tunable bandwidth.
Highly supportable	Ultra-reliable, no wear-out items, selected redundancy, graceful degradation.

Table 5.1. Navy ship radar requirements. [After Ref. 13, Fig. 5]

Such features enable the system to accurately track multiple targets without degrading its search operation. Applying special weighting functions to the array elements one can achieve ultra-low sidelobes on all monopulse patterns. Using phased arrays we avoid using items prone to mechanical wear such as rotating antennas with large motors and bearings, or long waveguides easily subject to damage. In addition the graceful degradation of the phased array increases the reliability of the system.

Table 5.1 indicates the necessity of using a phased array system. It would seem from a first glance that a passive array using either a traveling-wave tube transmitter or a solid state transmitter could achieve the needed characteristics. However Table 5.2 indicates that both passive array radar configurations shown, fail to measure up to the active array radar in terms of detection performance and physical parameters [Ref. 13]. This is mainly due to increased power requirements of the passive array radar which demands increased cooling capabilities along with greater weight and volume to achieve the same detection range with the active one.

Microwave tube technology continues to advance providing more powerful, stable and wider bandwidth vacuum tubes that can enhance certain radar characteristics. However it is obvious that active phased array systems, are the most appropriate to provide the multifunction characteristic to a tactical navy radar. This choice requires the use of solid state technology at the present time. However published papers on a Microwave Power Module which combines solid state and vacuum tube technology, show that MPM's have the potential to further improve the active phased array capabilities. MPM has demonstrated superior performance over TWT and solid state amplifiers. The most important advantages are their wide bandwidth, and the ability to operate in high ambient temperatures which leads to less cooling requirements. However, present microwave technology is able to provide MPMs with output power only up to 100 W (continuous) in the frequency range 6 GHz to 18 GHz. This power level is not yet enough for our application, assuming we use a 4100 element/module array antenna. We require modules with approximate output power of 500 W.

Parameter	Passive Array		Active array
	TWT Transmitter	Solid-State Transmitter	
Peak Power	45 KW	66 KW	15 KW
Transmit Duty Cycle	33 %	33 %	33 %
Number of Array Modules	1,500	1,500	1,500
System Noise figure	2 dB	2 dB	3 dB
Peak 2-way Sidelobe	-60 dB	-60 dB	-60 dB
Prime Power for Transmitter + Array	53 KW	105 KW	27 KW
Weight for Transmitter + Array + Array Power Supply	1300 lb	1500 lb	440 lb
Normalized Detection Range	100 %	100 %	100 %

Table 5.2. Equal detection Range performance Comparison.

A study of the availability of the microwave device industry reveals that it is already able to provide solid state T/R modules operating at 2 GHz with output power of 500 W and in appropriate packaging for use in active phased arrays. Further investigation of currently available microwave devices is recomended. Valuable information could be obtained in this study from the Naval Research Laboratory, Code 6844, which is the central program manager of the Microwave Power Module development program [Ref. 7, 8 and 14]. It is common knowledge that achievements at the edge of technology are classified. Since this technology is constantly improving, results of the study in the subject area of this thesis could be improved with a new look in a few years.

The final results of this thesis show that presently available microwave device technology is able to provide the devices needed to realize a radar system with the characteristics described in Chapter III and summarized in Table 5.1. Today's realization of such a system will probably use solid state modules in an active phased array antenna.

APPENDIX. FET BIASING TECHNIQUES

The three major methods of biasing a Field Effect Transistor are described in the following section.

A. FIXED BIASING

In fixed biasing the FET "gate" is directly connected to a voltage source while the "source" is connected to ground (Figure 1a).

Using this fixed biasing approach, we can not achieve repeatable performance. That is to say if two devices with a wide range of characteristics are used, some of the circuits may not work. Similarly, if the pinch-off voltage changes, since the biasing voltage is constant we might fall in the cut-off region (case 2 in Figure 1b) or away from the pinch-off region. Variations of the pinch-off point will also cause variations of the noise figure, since for the same signal, moving too close to cut-off region will introduce noise. Therefore fixed biasing is not a good choice for our application.
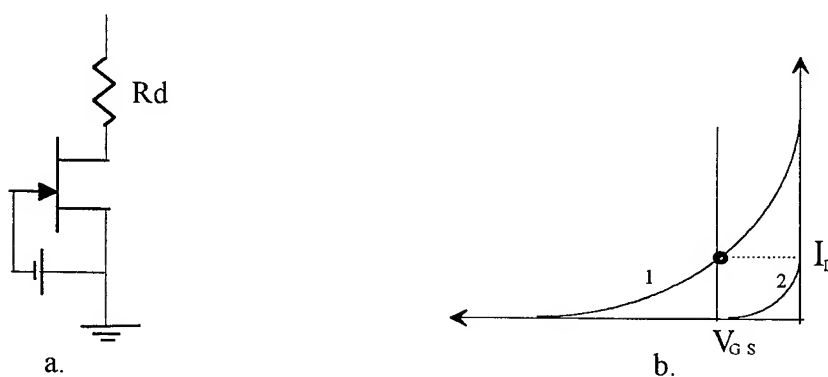

Figure 1. Fixed bias example.

B. SELF BIASING

In self biasing the "gate " is directly connected to ground while the "source is connected to ground through a resistor (Figure 2a).

Using self biasing it is easier to achieve repeatable acceptable performance but since I_D will vary (as in Figure 2b) the gain of the device will vary with the changes of pinch-off voltage. This is a better choice than fixed biasing but still suffers from a strong drawback.
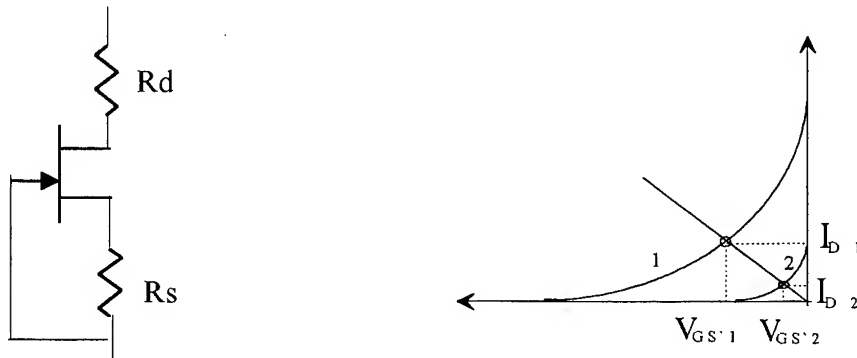

Figure 2. Self bias example.

C. COMBINATION BIASING

In combination biasing we use the advantages of the two previous techniques. The FET "gate " is connected to a voltage source through resistors or a voltage divider while the "source" is connected to ground through a resistor (Figure 3a).

Using combination biasing we can achieve repeatable good performance. The circuit characteristics will almost be the same, even if two widely different devices were used. This is due to the fact that I_D will be almost the same which will yield same gains even for significant changes of the pinch-off voltage (Figure 3b). This is the best biasing choice.

Specially in the combination biasing method controlling the slope of the load line we can trade off high gain and repeatable good performance for low noise figure. Choosing a slope for low I_D we can have high gain and repeatable good performance, but since the biasing point will be close to the cut-off region noise figure will be larger. Peaks of larger signals could push the device in cut-off region and the signal will be distorted at the output.

a.

b.
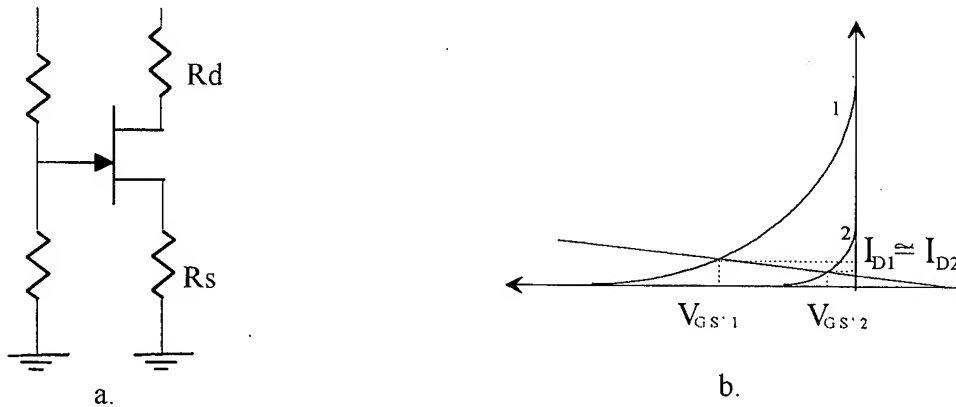
Figure 3. Combination bias example.

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